VACUUM FLASHOVER CHARACTERISTICS OF LAMINATED POLYSTYRENE INSULATORS

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Abstract

Laminated insulators consist of multiple layers of thin dielectric material stacked with metal films or thin metal layers. The formed stack withstands higher voltage than an equivalent, thick single-layer insulator. In the past materials like polyester, polycarbonate and polyamides have been used with values as high as 350 kV/cm for short pulse duration (50 to 100 nsec). Other materials, such as fuse silica, have also shown values as high as 175 kV/cm. These values have been accomplished with a straight dielectric wall stack of thin wafers. Such values make the lamination and stacking technique an excellent candidate for applications where bipolar pulses and low inductance restrict the use of the J.C. Martin standard 45° design.

We report experimental results of similar stacked insulator configurations using cross-linked polystyrene thin wafers of 0.010-inch and 0.020-inch thick and SS 304 0.0005-inch thick. The voltage used for testing is produced by a triggered Marx generator capable of 400 kV output with a rise time of 25 nsec and a pulse length of about 1.5 μsec. A voltage ring-up gain of about 20% is reported as the peak voltage and the RC line extension crossover as the averaged voltage. The results of testing different layer densities and different metal locations are described in this paper. We also describe the preparation and cleaning techniques that we have used, including plasma cleaning and pre-testing glow discharges.

I. INTRODUCTION

The most practical configuration for high voltage insulator bushings and interfaces for high power flow is the 45 deg (30 to 60 deg) geometry typically calculated and designed following J.C. Martin's criteria. Improvements to this basic concept have been accomplished by the use of different methods: cathode interface shielding, surface coatings, anode shielding, field shaping at the insulator vicinity, magnetic insulation, surface plasma conditioning and other less relevant methods. The greatest improvement is demonstrated by methods that modify electron trajectories, such as magnetic insulation, and methods that control secondary electron emission. In RF environments, metallic coating that suppress multipactoring result in the largest improvement for applications such as accelerator RF windows.

As power levels increase (higher voltage and currents with shorter pulse length), there is always a drive to reduce the size of the insulator interfaces. This arises because as the pulse length of the system is reduced, a typical water-to-vacuum interface, for instance, will be designed based in the high voltage vacuum side strength of the insulator stack rather than that of water. Water streamer formation times are typically larger than the time delay to breakdown in the vacuum insulator. In the search for lower inductance interface structures with better or comparable behavior as JCM designed insulators, stacked thin dielectric insulators are being tested with different materials.

Successful operation of stacked dielectric insulators have been previously reported using Kapton and Mylar as the dielectric material [1]. This paper describes similar stacked insulators using polystyrene as the base dielectric. Stacked insulators are made with thin dielectric wafers (usually 0.5 mm or less) and, with a metal interface (typically 0.05 mm or less), each pair is repeated until the desired height is accomplished. A thermoset (different types) is used between the dielectric and the metal wafer. These structures have been tested in vacuum [2], as vacuum interfaces and in the presence of an electron beam [3]. Samples ranging from 5 cm in diameter to 30 cm in diameter, solid and with a hollow center have been successfully tested. This paper reports a test matrix made of samples of 5 cm in diameter, and 1 cm thick, tested in preparation for a planned test sequence with samples of 45 cm and 75 cm in diameter.

II. THEORY

The theory behind the operation of these insulators has been explored from two points of view: 1) electron ballistic trajectory properties such as range and height [4], and 2) explosive emission from an arbitrary point and the

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14. ABSTRACT
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capacity of the stack to absorb the charge and its saturation properties [5]. With the first approach the electron range is calculated [tourriel] and used to determine the minimum dielectric wafer thickness, the electron maximum height determines if the metal, or the dielectric, is required to protrude from the surface. Other considerations, such as operating pressure and whether an electron beam is present or not, play a role on the sample configuration.

With the second design approach, explosive emission or the presence of an electron beam is assumed. The assumption is that the maximum current from the metal electrodes is space charge dominated. A minimum wafer thickness and/or the number of wafers required for the application can be calculated. Equation 1 represents charge accumulated as a function of surface interaction. A_n represents the section of surface area interacting with the electronic cloud as it moves toward the anode. q_n is the fraction of charge deposited on that section of the stack. Equation 1 comes from the assumption that a space charge dominated cloud of electrons is interfacing with a cylindrical dielectric surface made in a stacked fashion. Similar expressions can be developed for different insulator shapes and electrode configurations.

$$q_n \cong (qt(V) - q_{n-1})\frac{A_n}{At - A_{n-1}}$$

where: (1)

$$A_n \cong 2\pi x^2 \left\{ \cos\left[\tan^{-1}\left(n\frac{y}{x}\right)\right] - \cos\left[\tan^{-1}\left((n-1)\frac{y}{x}\right)\right]\right\}$$

To complement this approach, testing is in progress to determine the relationship between streamer tip photons and surface photoelectron production (surface impedance changes due to produced surface photoelectrons) [6]. A matrix of materials and surface conditions is being tested to measure photon density and wavelength characteristics, once this factor (how many photons and line width per surface photoelectron) is known it becomes an additive factor to the total surface volt-farad product characteristics.

III. TEST SETUP

The insulators were tested using a simple dual polarity Marx generator capable of a peak 600 kV, with an RC output waveform tailored by a simple resistive load. The output is measured using a voltage divider and a Tektronix 6015 voltage probe into a Tektronix 720 TDS. Figure 2 shows a typical waveform with the labels for what we labeled peak and average voltage.

The vacuum system consists of a stainless steel chamber with a Cryo-pump capable of 10^-8 Torr. The electrodes are made of SS-304 and are profiled to produce uniform field within 0.1% in a region of 12 cm diameter and roll-off with no enhancements at the edge region. Electrode material becomes relevant due to conditioning, when the

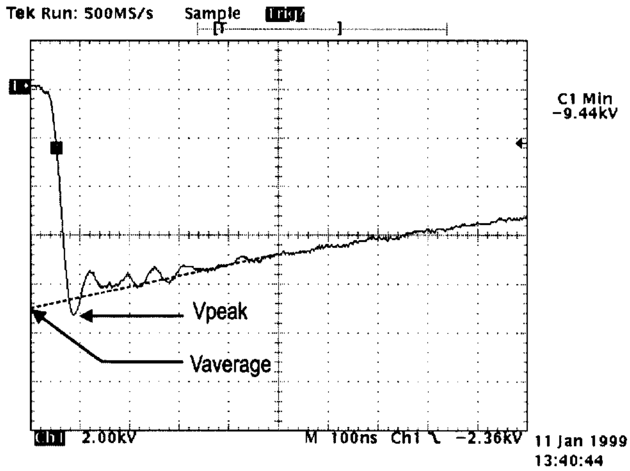

Figure 1. Typical output pulse, ±11 kv input charge giving an output of V_{avg} = 86 kv and V_{peak} = 94 kv. (Expanded time base.)

energy of the discharge is high [7}. At low energies, there are no conditioning effects introduced by the electrode material.

A very rigorous preparation and cleaning procedure was followed. The idea is to remove all possible factors affecting the experiment, such as anode and cathode surface finish, anode and cathode material, residual gas, residual surface contamination, surface area and sample thickness. By using a "dry" vacuum (Cryo-pump as compared with a "wet" vacuum such as a diffusion pump system), we expect to remove one more possible factor affecting surface performance.

IV. SAMPLE PREPARATION

Separate preparation and cleaning procedures for the electrodes and the samples were rigorously followed throughout the testing of the samples here reported. Three pairs of electrodes were used. Each set was used for one test sample and then re-polished. Each sample was inspected before and after each test. Below is the cleaning procedure for the samples, the electrodes were polished using 1500 emery.

1. Final wet sand with 1500grit silicon carbide paper and Cool Tool ™ water-soluble cutting fluid.
2. Clean with Isopropyl alcohol and a lint-free wipe.
3. Ultrasonic clean in Isopropyl alcohol for 5 minutes.
4. Blow-dried with nitrogen.
5. Glow discharge in the test chamber at 5.0 $^{-2}$ Torr, 3ma for 15 minutes.

A low-pressure nitrogen glow discharge was used as a final step to ensure cleanliness of the electrode sample set up. In fact, if the glow discharge showed to many 'bright" spots, indication of dust or whiskers burning, the sample will show a dramatically low voltage standoff. By using the glow discharge visual characteristics we were able to have an idea of the cleanliness of the system.

V. SAMPLE FABRICATION

Samples are made of the same material and by the same company. The samples tested were made with cross-linked polystyrene made by C-Lec (Rexolite). The material was supplied in sheets of 0.5 mm and 0.25 mm in thickness. The samples were made following one procedure, except one group that was cut with a high-pressure water jet. The typical procedure involves pre-cutting the samples in 6- to 6.3-cm squares, metal wafers and thermoses material are cut the same way. The material is cleaned and pre-assembled in a clean room and then the stacked form is inserted into a hollowed aluminum block with a wall-to-material gap of about 0.5 mm for thermal expansion. The aluminum block is black anodized to provide a smooth non-sticky surface and reduce sizing during pressure application. The assembly is pre-pressurized and allowed to stabilized overnight. The next day the assembly is pressurized and heated to thermoses manufacturer recommended parameters. Once cured, the sample is removed and machined to its final diameter and ready to its final surface preparation. A significant observation was that all samples pre-cut with a water jet performed better than those cut using mechanical means, such as a lathe and cutting tool. Testing was initiated with samples made out of solid Rexolite with a cylindrical face. These samples were prepared following the same procedure. The alternate fabrication method used was to stack and bake 30-cm square sections at the same time. Round sections close to the final sample diameter were then cut from the square block using a high pressure water jet. Both procedures have been used to produce samples of a variety of diameters and thickness.

VI. TEST RESULTS

Testing produced trends that correlated very well with results previously obtained using Mylar and Kapton. Data indicates that there is a "distance" or separation between metal lamination that produces the best results. Figure 2 (vertical axis kV/cm; horizontal axis is sample type) indicates the results from laminated samples made with 0.25 mm (0.010") polystyrene wafers. The two lines indicate average and peak voltages, as indicated in Figure 1. The upper line in Figure 2 corresponds to the average peak values from three samples (as indicated on Figure 1 as V_{peak}). The bottom line represents the average from three samples (as indicated on Figure 1 as V_{avg}). samples. Figure 3 indicates the results from samples made with 0.50 mm (0.020") thick polystyrene wafers. The two lines are as before: average and peak voltages, the lower line indicates capacitance per section in pF/ε. The capacitance dependence is not clear at this point. One speculation is that there may be a "formation" length for the initial streamer, this length corresponding to the distance from the cathode to the first capacitor layer and, thus, to the first section capacitance value.

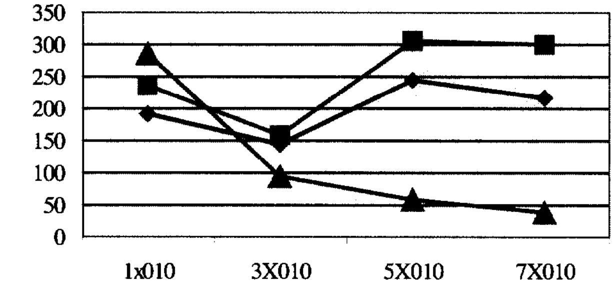

Figure 2. Comparison between electric field standoff (top two lines) and capacitance per section (bottom line with triangular data points) for the 0.25 mm samples. Vertical axis is kV/cm for the electric field and capacitance in pF/ε.

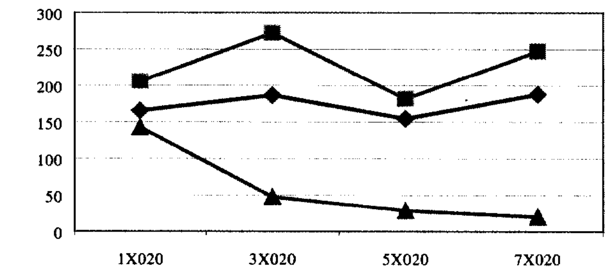

Figure 3. Trend between high voltage performance and capacitance for the 0.50 mm samples.

Figure 4 shows the individual results from most of the samples tested. Data shows significantly higher values for samples in the 5/10 group. In fact, one sample was measured at 425 kV/cm before flashover. At this level it is not clear if flashover is due to vacuum breakdown or insulator surface failure. Present research is focused on the 5/10 group to determine the factors that influence the data spread between samples. There may be a significant factor affecting the performance of the surface. Testing will continue since the spread between samples is considerable.

VII. CONCLUSION

Testing results indicate that careful surface preparation and extreme cleaning conditions are followed Laminated polystyrene can be taken to the vacuum breakdown values of the gap. The major significance of the laminating process is in the enhanced high voltage standoff and the surface effects after flashover. Surface preparation and pre-cutting methods may significantly affect surface performance. Dendrites and deep tracks are observed in a laminated sample with no metal wafers. The laminated sample with metal shows no significant damage and only a few marks on the metal surface.

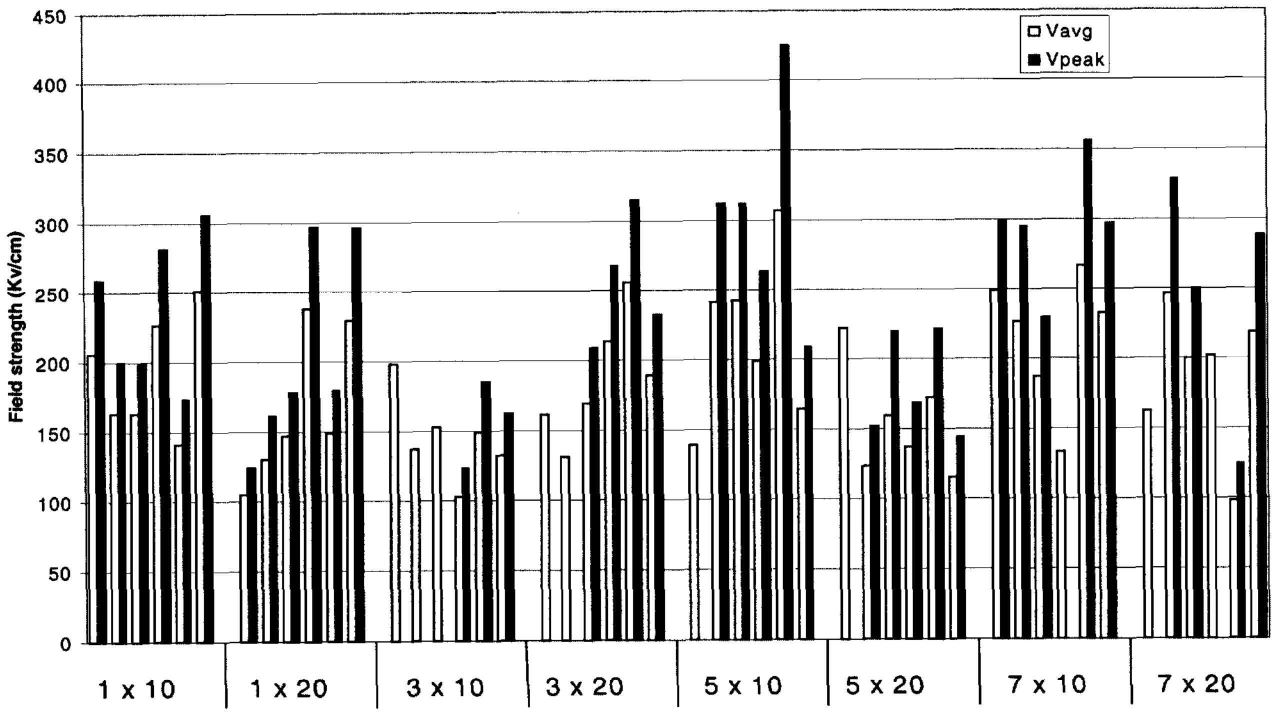

Figure 4. Individual results from most of the samples tested. Horizontal axis shows sample category.

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